Evaluating Prototyping Technologies for Product Design

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Abstract

Firms that design mechanical and electro-mechanical products confront a variety of difficult issues in their prototyping activities. For a given part, how can a choice among fabrication technologies be made? Where should investments in new prototyping technology be focused? How can new and existing prototyping technologies be evaluated? Our primary goal has been to develop a systematic method of evaluating prototyping processes in order to determine the best process for a given situation. A secondary goal has been to map the "space" of prototyping processes in order to determine future process development needs. Using data from a field study at the Kodak Apparatus Division, we have developed a systematic method for evaluating and selecting prototyping processes. Our data is drawn from (1) a user survey of prototyping perceptions and needs, (2) a survey to determine the importance of various prototype part performance attributes, and (3) estimates of the fabrication time, cost, and part performance for 104 parts and four prototyping processes.

Acknowledgements

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1. INTRODUCTION

Prototyping is one of the most critical activities in new product development. Firms that design mechanical and electro-mechanical products confront a variety of difficult issues in their prototyping activities. Some of these issues are tactical: For a given part, how can a choice among fabrication technologies be made? Some of the issues are strategic: Where should investments in new prototyping technology be focused? How can new and existing prototyping technologies be evaluated? We believe that there are useful conceptual frameworks and fundamental relationships that can be developed and used to support prototyping decisions, even though broad generalizations are likely to fail in some particular situations. Such a framework is particularly important today as lead times in product development become more critical [Fitzgerald87, Ulrich91] and as novel prototyping technologies emerge [Dickerson88, Kutay90, Lindsay90].

This paper describes research addressing these issues. Our primary goal has been to develop a systematic method of evaluating prototyping processes in order to determine the best process for a given situation. A secondary goal has been to map the "space" of prototyping processes in order to determine future process development needs.

Our basic methodology has been to study prototyping in the context of an industrial manufacturer. By using a data-directed approach based on existing parts and processes, we have been able to provide empirical support for a systematic method of evaluating and selecting processes. Our data is drawn from (1) a user survey of prototyping perceptions and needs, (2) a survey to determine the importance of various prototype part performance attributes, and (3) estimates of the fabrication time, cost, and part performance for over 104 parts and four prototyping processes. We focus on parts intended to be injection molded; the prototyping processes on which we concentrate are computer-aided design solid modeling (CAD), stereolithography (STL), computer numerical controlled machining (CNC), and rubber molding (RM).

The paper has four sections. In the balance of the introduction we define prototyping, present a conceptual framework for evaluating prototypes and prototyping processes, and describe our research focus. In the second section we present our approach and methodology. The third section details our results. The final section lists our conclusions and suggests areas for future research.

What is Prototyping?

Technically, a prototype is the first thing of its kind. But "prototype" has come to mean many different things in the context of product development. For the developer of commercial satellites, the prototype may be the final product. At the other extreme, the development of a new ballpoint pen may involve more than 10

prototypes before the design is finalized. Some prototypes are used to assess styling, some are used to perform life testing, some are used to verify fit. Other words frequently used to describe the function of a prototype include breadboard, model, and mock up. Each is an example of a prototype; each emphasizes a different aspect of what a prototype does. In our definition of a prototype we include both electronic and physical representations of the part or product.

In most cases prototypes are built to answer questions. In the engineering context, a prototype proves a technology or its application. In the marketing context, the prototype is a vehicle through which the marketer simulates customer response or finalizes design requirements. In the manufacturing context, a prototype proves a process or procedure. Effective prototyping requires understanding which questions to ask, when to ask them, and how to answer them.

Different types of prototypes are used in many different ways to address different types of questions. Electronic prototypes are often used for simulation. They may be subjected to finite element analysis, mass properties calculations, tolerance analysis, assembly analysis, or motion analysis. Some prototypes are used for verification; often analysis and simulation have been used to make many design decisions, and the prototype is used to detect unanticipated problems. Some prototypes are used to perform tests; they may be used for functional testing, customer perception testing, life testing, assembly planning, etc. Other prototypes serve as *crystal balls* to anticipate future problems; they may be used to prepare for tooling design, or to compare the evolving product with customer needs.

Framework

Product development professionals have highly varied prototyping needs. Designers concerned with styling have needs different from those of mechanism designers. Prototypes to support conceptual design have requirements different from those used in pre-production. The design of some parts may demand prototypes with very tight tolerances, while other parts may require special material properties. The required quantity is important in evaluating processes; some situations may require only one part, some may require 100 parts. Finally, in every case the user of a prototype cares to some extent about the cost and time required to procure a prototype.

To capture some of these issues, we evaluate prototyping processes along three dimensions: *part performance*, *unit cost*, and *lead time*. We view part performance as an aggregate measure of the fidelity of the properties of a prototype part, made with a particular process, with respect to the properties the part would have if it were made with the intended final production process. This performance measure is composed of attributes such as appearance, material properties, and dimensional accuracy. Using an importance weighting for each attribute, derived from a particular user's needs, the performance of a process with respect to each attribute can be combined into a single scalar part performance. Part cost and lead time could also be considered to be dimensions of performance, but since designers often think

of them independently of physical part attributes, we chose to separate them from other performance measures.

More formally, associated with each part, i, fabricated with a particular process, there is an associated cost, c_i, lead time, t_i, and performance vector $\mathbf{A}_i$. The performance vector for the part and process is composed of the performance of the process with respect to each of the attributes, a_j, or

$$\mathbf{A}_i = \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ \dots \\ a_{n-1} \\ a_n \end{bmatrix}$$

The set of attributes used to define the vector may vary depending upon the application or organizational context. Typical attributes might be strength, stiffness, density, color, surface finish, etc. Each a_j is assigned a value from 0 to 1 representing the degree of fidelity of the prototyping process to the final production process for the particular part. A score of 0 is a poor match and 1 is a perfect match.

For a given part, the attribute importance weighting vector, **W**, contains the importance weightings for each of the attributes, or

$$\mathbf{W} = \begin{bmatrix} w_0 \\ w_1 \\ w_2 \\ \dots \\ w_{n-1} \\ w_n \end{bmatrix}$$

Each w_j is assigned a value from 0 to 1 where 0 is unimportant and 1 is very important. For example, for a part to be used in a structural test, stiffness, strength, and dimensional accuracy may be very important while non-mechanical material properties like electrical conductivity may be unimportant.

The dot product of the performance vector and the transpose of the importance vector yields the scalar part performance, p_i.

$$\mathbf{A}_i \bullet \mathbf{W}^T = p_i$$

The determination of the appropriate weights in the importance vector is thus crucial to the use of this method. Each department in an organization could conceivably use a different weighting vector to determine performance of a process for its applications. A weighting vector might even be different for different parts within the same department (e.g. a duct versus a bracket). The weighting vector may vary with time as well; the vector used at the concept stage of development would differ from that used during the pre-production phase. For example, a

"breadboard" prototype intended only to verify a kinematic function might have an associated weighting vector that emphasizes dimensional accuracy, while a pre-production prototype intended to test consumer response might have an associated weighting vector that emphasizes surface finish.

In our study, we determined the relevant performance attributes and the importance weightings for a particular class of parts in a particular company. Then, based on estimates of the time, cost, and performance of four processes on over one hundred parts, we were able to determine the average performances, costs, and times for the processes. This information allows us to prescribe a prototyping decision procedure for this particular set of attributes and importance weightings.

Focus

We focus on the prototyping of plastic piece parts. All of our data were gathered at the Apparatus Division of the Eastman Kodak Company (KAD) in Rochester, New York. Although product design involves a diverse set of prototyping applications, processes, and needs, we focus on a particular class of prototyping problems in a specific industrial setting in order to generate meaningful results. While the specific results are valid only for this setting, the methodology can be applied to other types of parts and processes. Evaluating prototyping technologies for printed circuit boards, metal shafts, or food products would require performance vectors substantially different from those of plastic parts, but we believe the basic framework would remain valid and useful.

The Parts

All of the parts used in our study were intended to be plastic in final production. For over 85% of the parts, the final production process had been determined to be injection molding. For the balance of the parts, the final process had not been determined, or, in a few cases, other processes such as vacuum forming were to be used. The parts were obtained from a database of parts at the stereolithography laboratory at KAD, and were drawn from several types of products including photocopiers, medical imaging equipment, and printers. The parts varied in complexity, size, and shape. We believe that the part sample represents a uniform distribution of part types for injection molded parts in medium volume products. Figure 1 shows two typical parts from the sample.

The Processes

The study was based on four prototyping processes: computer-aided design solid modeling (CAD), stereolithography (STL), computer numerically controlled machining (CNC), and room temperature vulcanizing rubber molding (RM). It should be noted that the processes are not entirely independent: STL and CNC depend on a CAD model, and RM requires a master (often generated by STL or CNC). The processes are described briefly below.

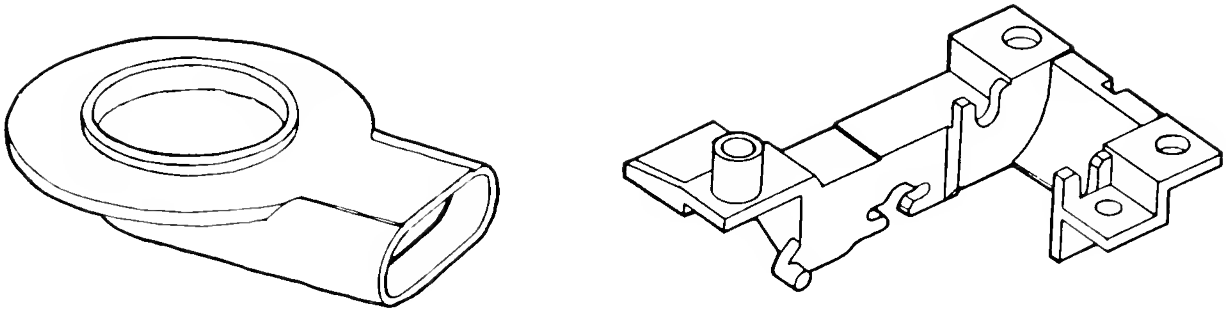

Figure 1: Sample parts.

CAD solid modeling. For our study, we assume that a part design exists; we base the prototype cost and time performance for CAD on the resources required to translate a defined design into a solid model. In many firms, solid modeling is becoming the standard means of creating, representing, and storing design data [Hurt89, Stix91]; in these settings, there would be no additional cost or time required to create a CAD solid model for prototyping purposes. As a baseline case, we include only the visualization and geometric reasoning capabilities of solid modeling. With enough time and money, simulation and analysis packages can be used to understand almost every performance aspect of a part without building a physical prototype. At KAD these tools are typically used on only the most critical parts in a product. For this reason, and because there is so much variability in both the available software and in user skill, we confine our definition of CAD as a prototyping process to the basic functionality of a solid modeler. In the final section of the paper we discuss a set of clear opportunities for CAD to supplant physical prototyping.

Stereolithography. Stereolithography is a process by which solid plastic parts are created by building a stack of cross sections. Each cross section is fabricated by using a laser to cure a thin layer of a liquid ultraviolet-sensitive photo-polymer. Estimates of STL parts were made based on the performance of a 3D Systems, Inc. SLA500 machine. There are currently only a few polymers that can be used in the stereolithography process [Lindsay 90]. Fabricating an STL part requires a CAD model of the part.

Computer Numerically Controlled Machining. Evaluation of CNC parts assumed fabrication on a lathe or five-axis milling machine. Although many parts could be built on a three- or four-axis machine, five axes were assumed in order to minimize the number of fixtures and setups. Some of the parts required setup on both a lathe and a mill [Ford90].

Rubber Molding. Many plastic parts can be made by casting a polymer such as polyurethane in a silicone rubber mold. This process involves first casting the rubber mold around a part master and then filling the resulting mold cavity with the desired part material. Molding compounds are available that approximate the properties of many thermoplastics used in injection molding. At KAD, both CNC and STL are used to create the part master.

2. APPROACH AND METHODOLOGY

We used estimates and surveys to answer the following questions for our focused domain:

- What attributes are important for prototype parts (i.e. What attributes make up **A**)?

- What are the relative importances of these properties (i.e. What is **W**)?
- How well do the different processes perform with respect to these importances (i.e. What are the values for the a_j 's in **A**?)?
- What are the lead times and costs for the processes (i.e. what are c and t)?

A *User Survey of Prototyping Perceptions and Needs* was used to identify critical attributes. An *Attribute Importance Survey* was developed to establish the importance of each attribute at various phases of development (the values of the elements of **W**). A *Process/Part Evaluation* was designed to determine cost, lead time, and process performance for each attribute (the values for c, t, and the elements of **A**).

User Survey of Prototyping Perceptions and Needs

In order to gather general information about prototyping perceptions and needs, we conducted an informal written survey of 24 designers, engineers, and managers at 6 of the lines of business within Eastman Kodak. The survey asked for such things as a definition of "prototype", the purpose of prototypes within the organization, material and process needs, standard procedures for procuring prototypes, and the characteristics of the ideal prototyping facility.

Based on the responses to this survey we identified the performance attributes given in the right column of Table 1. In order to simplify our presentation of the results, we have aggregated the attributes into four higher-level categories.

Table 1: Performance Attributes Identified in the User Survey

aggregate attributes	constitutive attributes
appearance	overall part appearance
strength/stiffness	strength stiffness
form accuracy	dimensional accuracy geometric accuracy surface finish feature definition
material properties (other than strength and stiffness)	hardness weight melting temperature opacity conductivity color

Attribute Importance Survey

A written survey was sent to over 900 designers, engineers, tool- and instrument-makers, and project managers at Eastman Kodak. 171 (18%) of the surveys were returned. The survey asked each respondent to rate the importance of each of the attributes in Table 1 at the concept, engineering, and pre-production phases of development. At each phase, each attribute received a ranking from "unimportant" to "very important." The survey also requested information about the respondents' primary function (design, engineering, or management) and discipline (mechanical, electrical, optical, etc.). Of the 171 respondents, 143 identified themselves as involved in a "mechanical" discipline, 12 specified "electrical," 7 specified "optical," and 11 specified "other." Of the 143 in the mechanical discipline, 52 specified that "design" was their primary function, 63 specified "engineering," 18 specified "management," and 9 indicated "other." The respondents were selected from a mailing list of users of the Unigraphics CAD system at Eastman Kodak and from personal contacts made by the authors. A copy of the survey is shown in Appendix A. These data were used to establish the importance weighting vector for the study.

Process/Part Evaluation

Parts were evaluated along the three dimensions —performance, time, and cost— for each of four processes. Estimates of time and cost were made by experienced employees at KAD. In order to reduce variability due to communication issues, the majority of the estimates were made with the part in hand. Table 2 lists the assumptions upon which the estimates were based and the components of the time and cost estimates. The performance of each part was calculated using the attribute rating system described in Section 1, *Framework*, and the attributes listed in Table 1.

Table 2: Components of Estimates and Assumptions.

components of cost	CAD	STL	CNC	RM
labor	• 1 skilled CAD operator	• 1 skilled CAD operator • 1 skilled SLA operator	• 1 skilled CNC programmer • 1 skilled CNC operator	• 1 skilled mold-maker
machine	• CAD workstation	• SLA500 • curing oven	• 5-axis CNC mill • CNC lathe	• vacuum pump • ventilation hood
materials		• Ciba-Geigy resin	• fixture material • part material	• mold material • resin for part • gloves, syringes, etc. for handling resins

components of time	• translation of drawing or defined concept to CAD solid model	• generation of support structures • translation and manipulation of build files • build time • cure time • hand finishing	• definition of tool path • debugging of program • setup time • run time • hand finishing and/or post machining where needed	• design of mold • fabrication of inserts, supports, etc. • fabrication of mold • mold cure time • pouring of part • part cure time

A number of factors make estimating processing time and cost difficult. First, the reliability and consistency of the estimator had to be established. In many organizations estimating is still more art than science; often the estimators would produce one estimate then start over as they realized a more elegant solution to the fabrication problem. Second, we had to define where one process finished and another started, and we had to define the "average" target level of performance for each process. For example, a stereolithography part destined for the paper path of a copier required more hand finishing time than a similar stereolithography part designed to hold rolls of film. Third, the skill levels of the operators were also an issue. Fourth, we often found variations within a given process; a given part can often be fabricated by a given process a number of different ways. Finally, the capacity utilization of a process determines the time a part will spend waiting for the process. For the time estimates, we assumed that capacity utilization was low enough that the queueing effects were negligible. This will only be true in organizations that allocate enough capacity to prototyping that jobs move through the shop without contending for resources.

Rather than spend a great deal of time calculating an exhaustive estimate with a very tight margin of error, the estimators were instructed to maintain consistency between parts; the accuracy of one part relative to another was more important than the estimate for any given part. It should also be noted that the estimators were explicitly told that they would not be held to their estimates (we tried to decouple the estimating process from the organizational incentives within KAD). Also, the estimators were familiar with many of the parts; in some cases they had fabricated the parts within the past year.

For each part, one of us (Wall) rated performance in each attribute category on a scale of 0 to 1. The basis for the rating was the answer to the question, "How well does the prototype part approximate the production part?" In some cases, the question was, "How much information does the prototype part tell about the production part?" For some of the attributes [and for the CAD process] one question makes more sense than the other. A score of 1 meant that the prototype part matched the production part for that attribute (or that the prototype part provided as much information as the production part). For example, Tables 3a & 3b show the estimates for and evaluation of the two sample parts in Figure 1.

Table 3a: Example of Estimates
(times in hours:minutes)

process	process component	"bracket"	"duct"
CAD	time to create solid model	4:00	6:00
STL	time to generate support structures	1:00	0:15
	time to prepare files for slicing & building	0:30	0:15
	time to create build file	0:15	0:10
	time to build part on SLA500	3:45	5:00
	time to cure part in UV oven	2:00	1:00
	time to hand finish	2:00	1:00
CNC	time to program	14:00	7:00
	time to setup and debug	12:00	5:00
	time to run 1 part	1:45	1:30
	time to build fixture	0:00	3:00
	number of special fixtures	0	1
RM	time to build special tooling	8:00	0:30
	time to setup and fabricate mold	12:00	10:00
	time to pour one part	1:00	0:45
	time to cure one part	12:00	12:00
	time to cure mold	32:00	32:00
	qty of part material	10 cubic inches	9 cubic inches
	qty of mold material	150 cubic inches	132 cubic inches
	number of pieces to mold	2	2

Table 3b: Examples of Evaluations

	"bracket"				"duct"			
attribute	CAD	STL	CNC	RM	CAD	STL	CNC	RM
strength / stiffness	**0**	**0.55**	**0.9**	**0.85**	**0**	**0.65**	**0.95**	**1.0**
strength	0	0.5	0.9	0.9	0	0.6	0.9	1.0
stiffness	0	0.6	0.9	0.8	0	0.7	1.0	1.0
form accuracy	**0.83**	**0.85**	**0.85**	**0.98**	**0.75**	**0.85**	**0.83**	**0.95**
dimensional accuracy	1.0	0.8	0.9	0.9	1.0	0.8	0.9	0.9
geometry	1.0	0.9	0.7	1.0	1.0	0.9	0.8	0.9
surface finish	0.3	0.8	0.9	1.0	0.1	0.8	0.8	1.0
feature definition	1.0	0.9	0.9	1.0	0.9	0.9	0.8	1.0
appearance	**0.5**	**0.8**	**0.9**	**1.0**	**0.7**	**0.8**	**0.8**	**1.0**
overall appearance	0.5	0.8	0.9	1.0	0.7	0.8	0.8	1.0
material properties	**0.23**	**0.52**	**0.98**	**1.0**	**0.23**	**0.37**	**0.98**	**1.0**
hardness	0	0.9	1.0	1.0	0	1.0	1.0	1.0
weight	0.9	0.8	0.9	1.0	0.9	0.9	0.9	1.0
melting temp	0	0	1.0	1.0	0	0	1.0	1.0
opacity	0	0.3	1.0	1.0	0	0.3	1.0	1.0
color	0.5	0	1.0	1.0	0.5	0	1.0	1.0
conductivity	0	0	1.0	1.0	0	0	1.0	1.0

Once these evaluations were performed for all 104 parts, the part performance ratings, the cost estimates, and the time estimates were averaged to rank the processes in terms of performance, cost, and time.

3. RESULTS

Summary of Results

The results of the study are summarized in Figures 2-10. Figure 2 shows the importance of each aggregate prototype attribute based on replies to the Attribute Importance Survey. (The individual attributes that make up the aggregate attributes shown in Table 2 are listed in Table 1.) Note that the importance of each attribute increases as the project progresses and that time was rated most important at every phase of product development. As expected, there are differences in the importances indicated by the respondents. There is also some difference in the mean responses among respondents who classified themselves as "engineering" or "design" and those who claimed "management." Depending on the goals of the prototyping evaluation process, a weighting vector could be defined for a single individual or for a particular group of individuals. For presentation purposes, we created a weighting vector by averaging all of the responses. The resulting vector is $W^T = \left[0.73\ 0.74\ 0.53\ 0.49\right]$ for the attributes strength/stiffness, dimensional accuracy, appearance, and material properties other than strength and stiffness.

The results of the lead time estimates from the Process/Part Evaluation are shown in Figure 3 for a lot size of 1 and in Figure 4 for a lot size of 25. The results of the cost estimates from the Part/Process Evaluation are shown in Figures 5 for a lot size of 1 and in Figure 6 for a lot size of 25. Note that the horizontal axes in figures 3 through 7 do not represent continuous variables, rather they are part numbers 1 through 104 evenly spaced along the horizontal axis. The values for each process are connected together by lines to make the data legible and not to suggest a continuous function. The data in figures 3 through 7 were all sorted in order of increasing lead time for the CNC process and a lot size of 1. Lead time to fabricate a single part for each of the processes depended loosely upon part complexity (where complexity was related to the number of geometric primitives needed to define the part) and so the parts are roughly ordered in terms of increasing complexity.

The scalar part performances for each part and process are plotted in Figure 7. The scalar performance of each part was calculated using a performance vector (A), based on the attributes in Table 1, and the weighting vector, $W^T = [0.73\ 0.74\ 0.53\ 0.49]$, derived from the Attribute Importance Survey. The data were sorted as in Figures 3-6.

Averaging of the part performances for each process yields the average process performance results shown in Figure 8. For each process, the time and cost scores are normalized values relative to the other processes, where 1 is fastest/least expensive and 0 is slowest/most expensive. Time and cost ratings are for a lot size of 1.

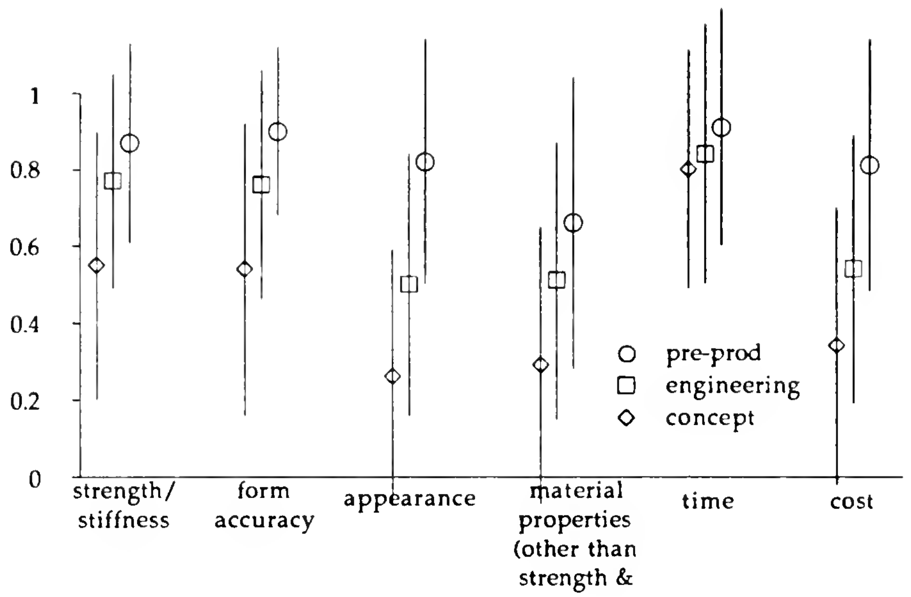

Figure 2: Mean and Standard Deviation of the Importance of Performance Attributes, Time, & Cost at Various Phases of Development

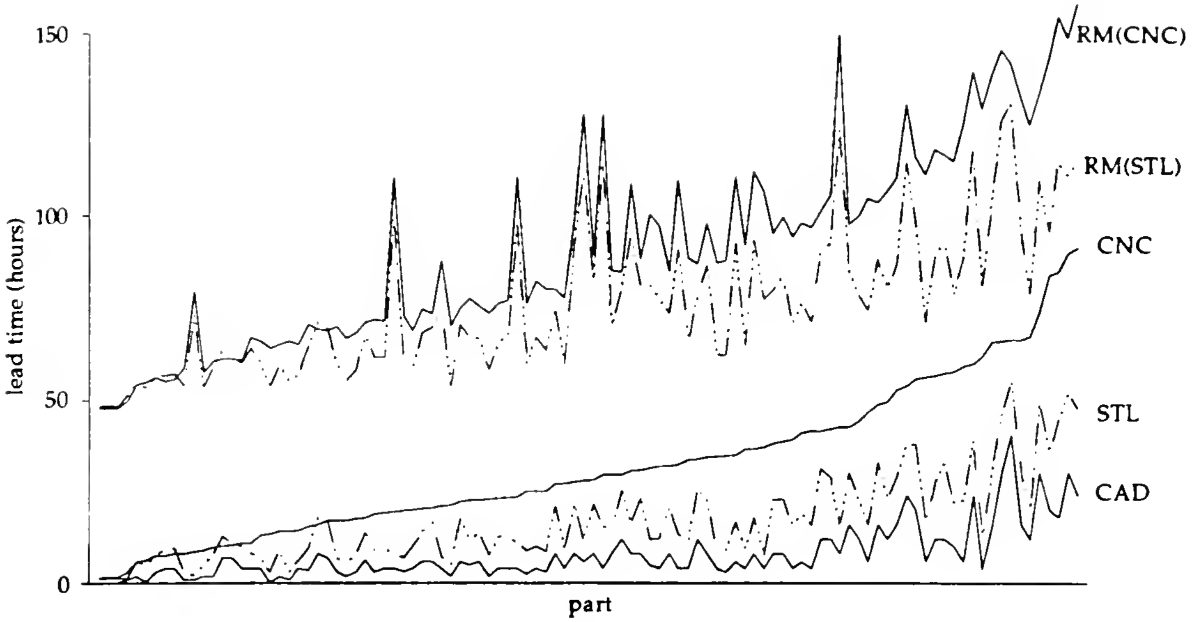

Figure 3: Lead Time for Each Part (lot size of 1)

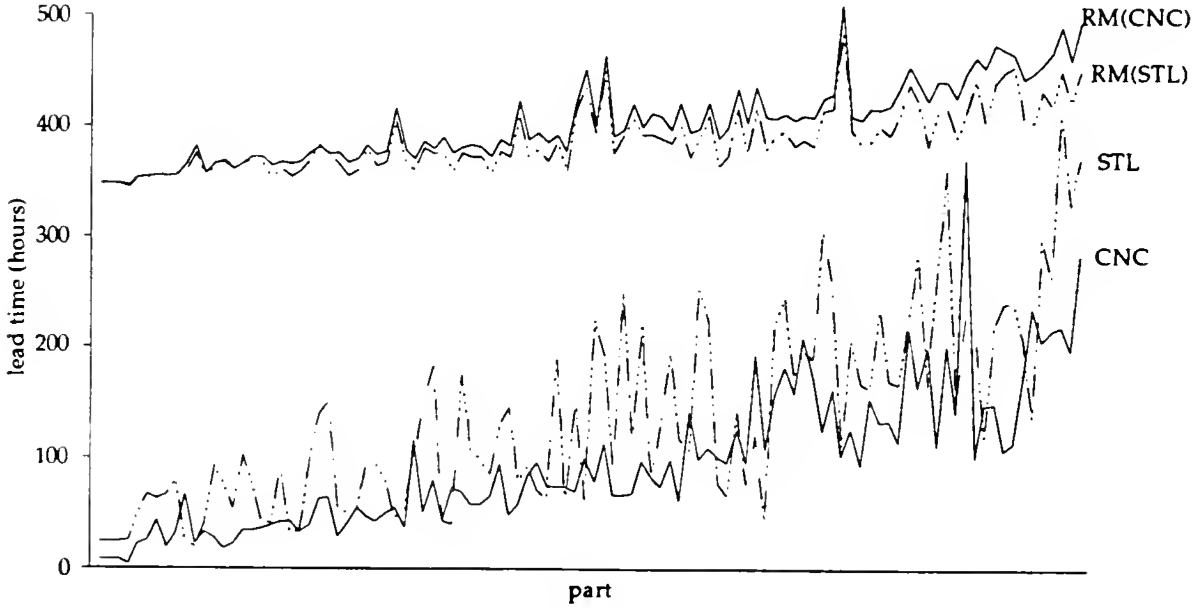

Figure 4: Lead Time for Each Part (lot size of 25)

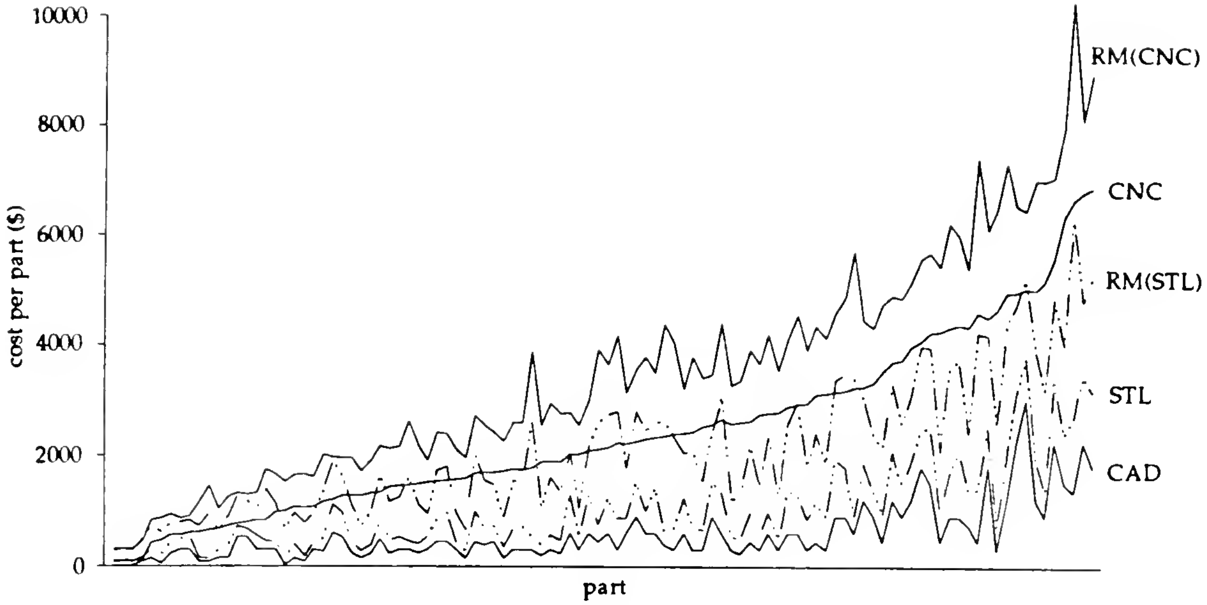

Figure 5: Cost of Each Part (lot size of 1)

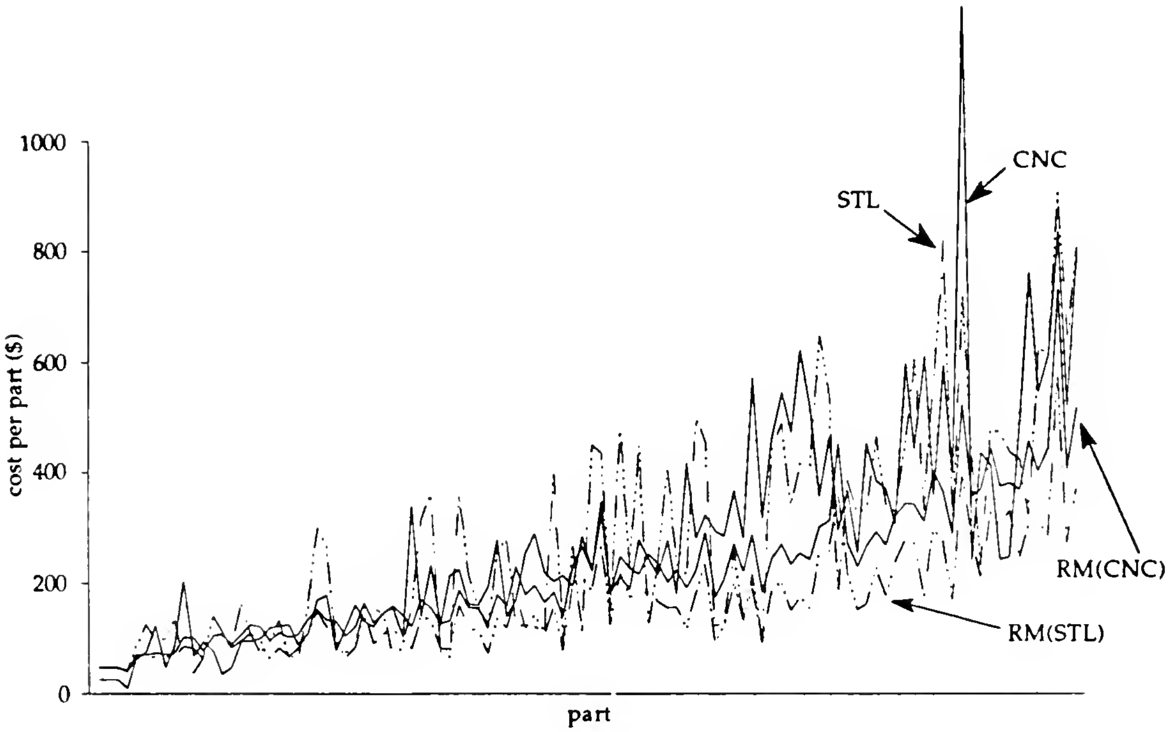

Figure 6: Cost of Each Part (lot size of 25)

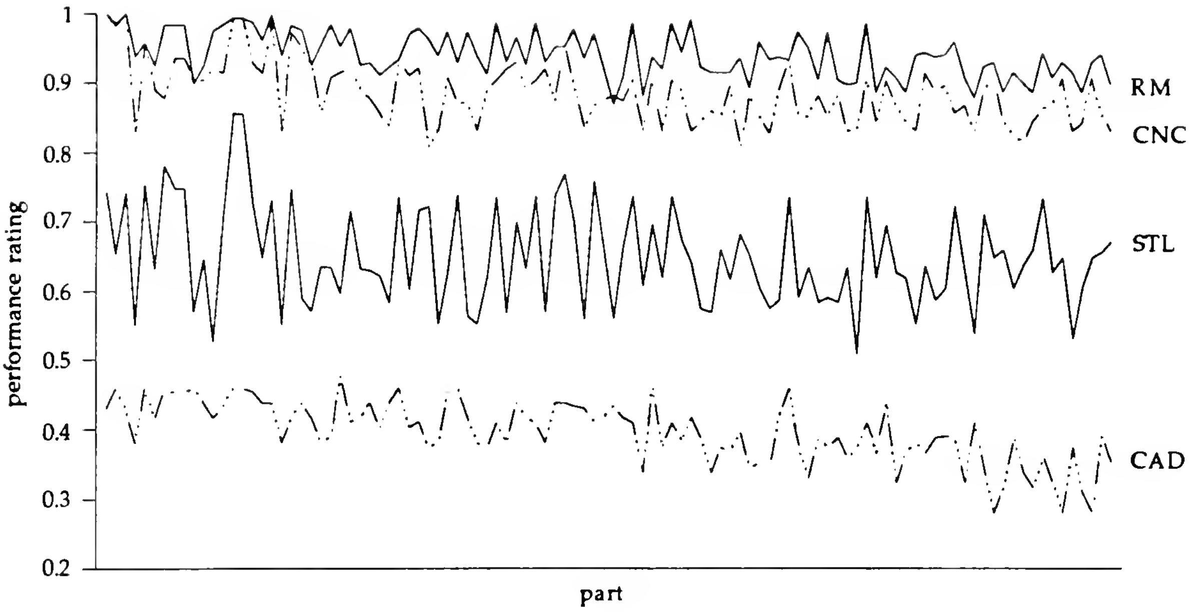

Figure 7: Aggregate Performance of Parts

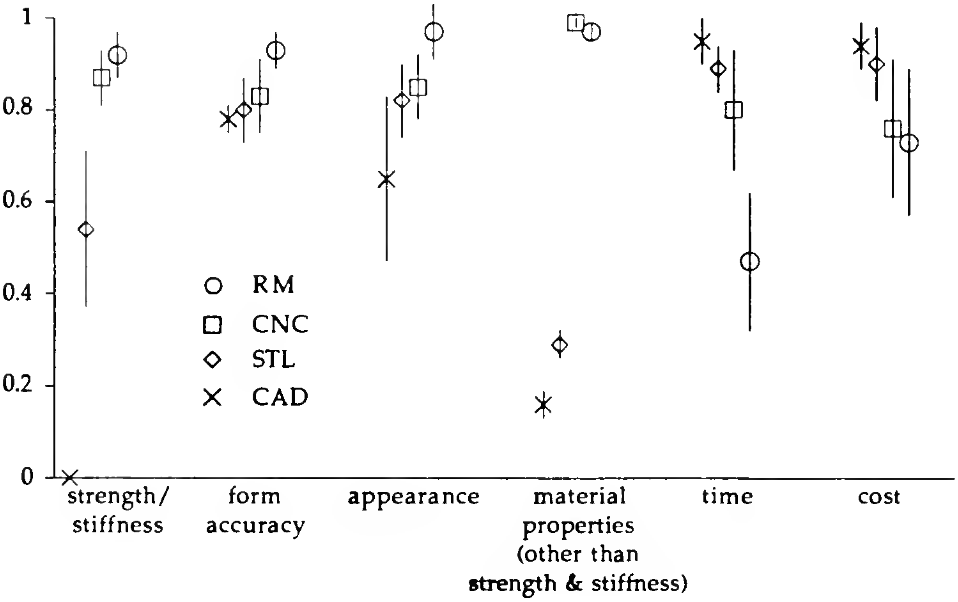

Figure 8: Mean and Standard Deviation of Performance, Time, & Cost Ratings for Different Processes

Finally, Figures 9 and 10 illustrate the quantitative relative time- and cost-performance of each process based on lot sizes of 1 and 25. Note that because the *relative* ordering of the cost and time values for each of the processes is roughly the same regardless of the parts (indicated by infrequent crossing of the process lines in figures 3 through 6), the large standard deviations in figures 9 and 10 do not imply an inability to predict relative overall process performance. Rather, a part costing substantially less than the mean to produce by STL will likely also cost substantially less than the mean to produce by CNC.

Interpretation of Results

A decision among processes for prototyping a particular part can be made based on the data in Figures 8-10. The first step is to determine, using Figure 8, which processes will provide the information required of the prototype. Then Figures 9 & 10 are used to determine which of these processes is best in terms of time or cost for a given lot size. For example, the bracket shown in Figure 1 must be made of a conductive material. Based on this fact and the process ratings in Figure 8, the alternative processes are RM(CNC), RM(STL), and CNC. If we assume that 25 parts are required and that time is the driving factor in the process decision, Figure 9 shows that CNC is the preferred process. If we extend the example and assume instead that cost were the driving factor, Figure 10 shows that rubber molding from a stereolithography master is preferred.

Table 4 summarizes the process decisions for a small set of decision drivers. The table uses time, cost, the four aggregate attributes, and lot size as the factors that determine which process to use. Each entry in the table was made by (1) narrowing the set of possible processes to those that will perform well with respect to a critical attribute (using Figure 8), and (2) determining the best time or cost performance for the appropriate lot size (using Figures 9 & 10). The parenthesized entries in the "form accuracy" row indicate the preferred process if a physical part is required. In some cases either STL or CNC would be the "preferred" process; whereas the average values indicated one process, the standard deviations were large enough to suggest that the other might be a viable alternative. In these cases alternatives are provided in parentheses.

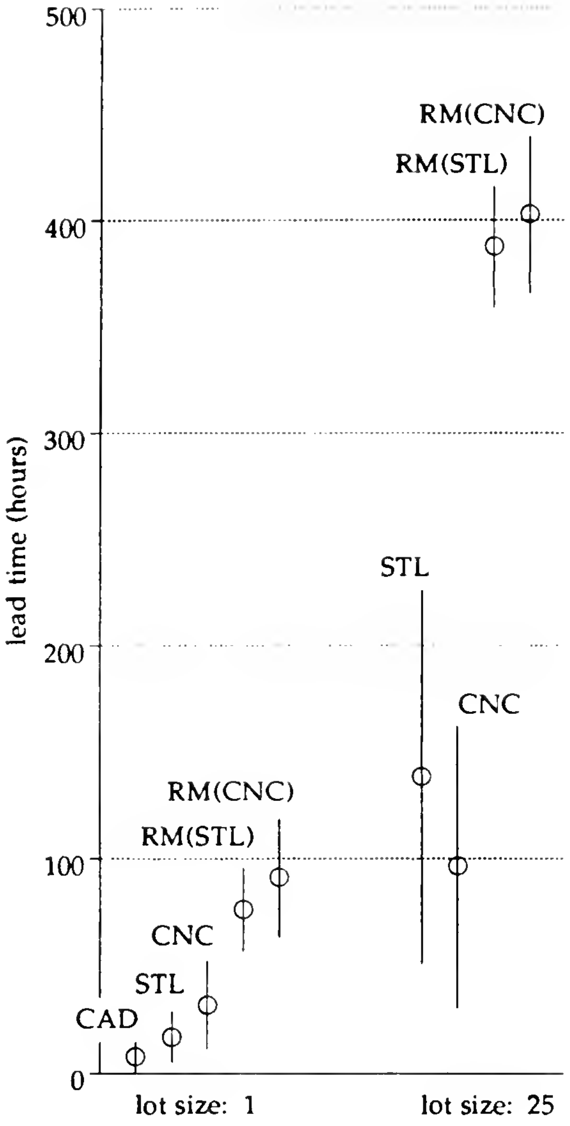

Figure 9: Mean and Standard Deviation of Process Lead Times

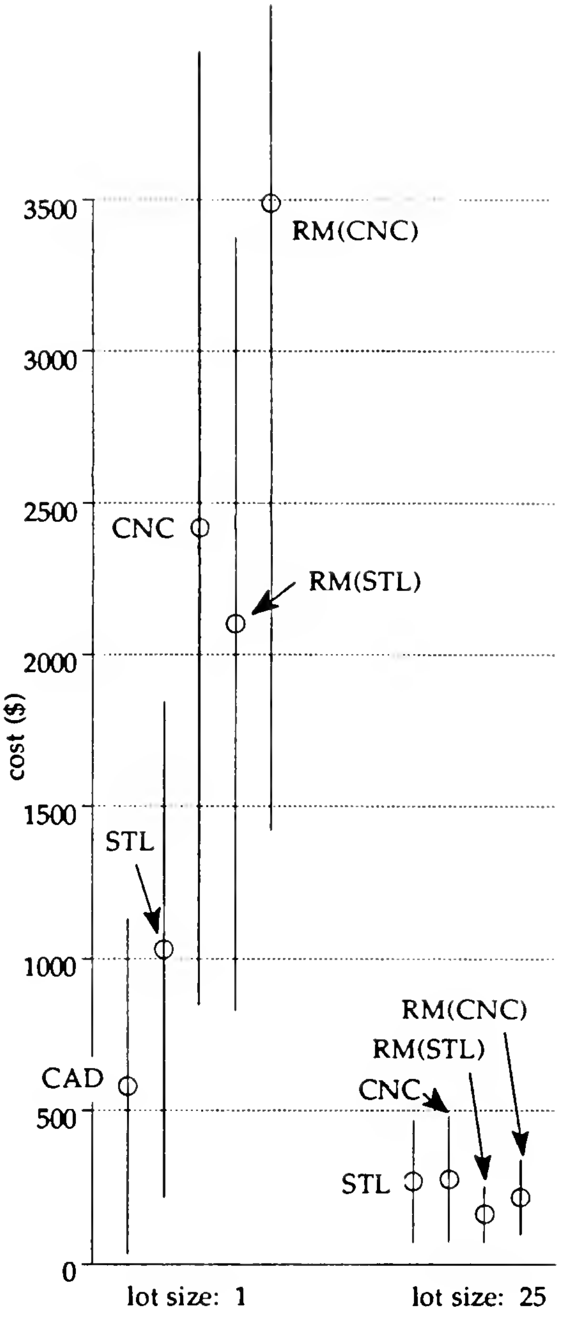

Figure 10: Mean and Standard Deviation of Process Costs

Table 4: Preferred Prototyping Processes Based on Results.

	Cases where time is the driver		Cases where cost is the driver	
critical attribute	Qty: 1	Qty: 25	Qty: 1	Qty: 25
strength/stiffness	CNC	CNC	RM from STL (CNC)	RM from STL (CNC)
form accuracy	CAD (STL)	CAD (CNC)	CAD (STL)	CAD (RM from STL)
appearance	STL	CNC	STL	RM from STL (STL or CNC)
material properties	CNC	CNC	RM from STL (CNC)	RM from STL (CNC)

Table 4 lists the guidelines for a particular class of parts, processes, attributes, and lot sizes, but the procedure described above can be applied more generally to different classes of parts, attribute sets, weighting vectors, and lot sizes. The procedure for evaluating processes is thus:

(1) Determine which of the performance attributes are most critical.

(2) Determine which processes produce parts which have adequate performance for these attributes.

(3) Choose between processes based on time, cost, or both (depending on the relative importance of time and cost for the part procurement).

4. CONCLUSIONS & DIRECTIONS FOR FUTURE WORK

We have evaluated a set of prototyping technologies for a focused domain of applications. In doing so we have demonstrated a methodology for assessing and representing performance needs for a prototype part and for evaluating different processes with respect to these needs. We have been able to prescribe the most promising prototyping processes for a specific situation, given the performance characteristics that are most important for the part and given either a time- or cost-driven decision process. In the course of this study, we have also developed insights into some of the broader issues in prototyping. In this final section we present some of these insights and discuss some areas for future work in supporting design decision making and in improving the prototyping processes themselves.

Insights from the Prototyping Study

Time is almost always very important to the customer of a prototyping process. This result resonates with recent emphasis on shortened product development cycles. It is also consistent with findings in [Ulrich91] indicating that in some product contexts, the economic impact of lead time dominates materials cost and

labor cost issues in design decision making. The criticality of time suggests that firms should maintain enough prototyping capacity that queueing delays do not influence the lead time of the product. Justifying the associated capital outlay is difficult without some explicit estimate of the value of prototyping lead time to the organization.

Conventional CNC machining is among the best prototyping alternatives. For plastic parts, process performance depends on the details of the application. Nevertheless, it is interesting that the best choice of prototyping technology (Table 4) is dominated by CNC machining for the time-driven case. We have observed that many designers are surprised by this result because the trade literature has given a lot of attention to so-called *rapid prototyping* processes. Although we see tremendous opportunities for rapid prototyping technologies like stereolithography, machining is often the best available prototyping technology. In our subsequent discussion of process development we will articulate the process developments that may change the relative strengths of these processes.

Rapid is a relative term for prototyping. The promise of instant models from CAD data is still largely unfulfilled. The average lead time to acquire a physical prototype from stereolithography was 9.3 hours for our part sample, assuming that there was no queue for the stereolithography machine. However, in general STL parts can not be used in functional tests because of the relatively poor material properties of the stereolithography resins. The average time to acquire a part with good strength and stiffness properties was 24.2 hours (CNC machining). This can be as long as three calendar days for a one-shift prototype shop.

Processes tend to perform better on simple parts than complex parts. This result is intuitive but because we have not displayed the geometry of each of the 104 parts, it is not clear from the presentation of our data. In general, the differences *between processes* were greater than the differences in time, cost, and performance *between parts*. (In fact, this is what allows us to make the part-independent recommendations in table 4.) Nevertheless, simpler parts (measured by the number of geometric primitives in the CAD file) in general obtained higher performance ratings. One implication of this observation is that part designers might consider simplifying or tailoring part geometry in anticipation of prototyping requirements. A related idea was suggested for analysis tools in [Suri89] and seems equally appropriate for prototyping.

There is still no substitute for a skilled operator. Many views of "desktop manufacturing" neglect the knowledge and skills of machine operators by trying to make the designer omniscient. We found that many ideas are born as designers interact with fabricators.

Supporting Design Decision Making

A complex electromechanical product may contain thousands of parts with diverse intended functionality and diverse intended final production processes. When

integrated into the design process, a rough-cut prototyping process evaluation system could be a powerful tool for the designer, engineer, and manager. A computerized implementation may be imagined as follows. As the project is initiated, attributes and importances are defined and agreed upon for different classes of parts. Decisions about the number of prototypes that will be required at various stages of the process are established. This information can be used to inform the designer what the recommended prototyping process is and what the associated time, cost, and performance measures for the current part or assembly are. The designer could then add this information to the information available for other evaluation criteria in order to make better detailed part design decisions. As the needs of the project evolve, the project team might change the desired lot sizes or call for re-evaluation of attribute importances. Such a tool would fit naturally into a group design environment utilizing comprehensive, interactive design software.

Improving Prototyping Processes

Figures 11 and 12 and Table 5 summarize the process cost and time components for CNC, STL, and RM. Along with the average process performance results shown in Figure 8, these results help to focus prototyping process development. Note that in this case the STL and CNC figures do not include the time or cost to create a CAD model and the RM figures do not include the time or cost to fabricate a master. Note that the lead times for 25 parts could be reduced substantially in some cases by parallel processing. For example, if the parts are small enough, more than one can be built simultaneously on the SLA500 platform. Or, if more than one master is available, multiple parts can be molded simultaneously.

Table 5: Average Lead Times (hours)

	STL	CNC	RM
1 part	9.3	24.2	59.2
25 parts	130.9	88.8	370.9

Each of the processes has weaknesses and could benefit immensely from research and development. The figures illuminate important areas for process development:

- Nearly 50% of the time to fabricate one CNC part is programming time. If that is reduced (by automated generation of cutter paths, for example) then CNC becomes even more useful as a prototyping tool.
- STL performs very well on average except where material properties are critical; the available resins are too limited. An improvement in resins would immediately make STL the dominant prototyping technology for plastic parts.
- CAD is very fast and has high geometrical accuracy. But, it falls short in evaluating strength, stiffness, and other material properties. We did not assess finite element analysis methods of prototyping which address some of these weaknesses. However, the state-of-the-art in

simulation is still an inadequate substitute for a physical model. Advances in non-linear, dynamic simulation of multiple parts would enable CAD to emerge as an even more important prototyping technology.

- Rubber molding is an attractive process because it can be used for small scale production. But the process is slow. There is a clear need for either fast-curing polymers or for technologies that allow thermoplastics to be molded from quickly-procured tooling. Developments in spray metal tooling may eventually enable the fabrication of batches of 100 plastic parts relatively quickly [Weiss90].

We hope that the specific results from our study soon will be obsolete because of rapid advances in process development. We believe, however, that the methodology we have developed can be used to make intelligent and rational prototyping decisions as processes change and in differing product development contexts. The methodology supports the tactical decisions surrounding part design and choice of prototyping technologies as well as the strategic decisions surrounding investment in process development.

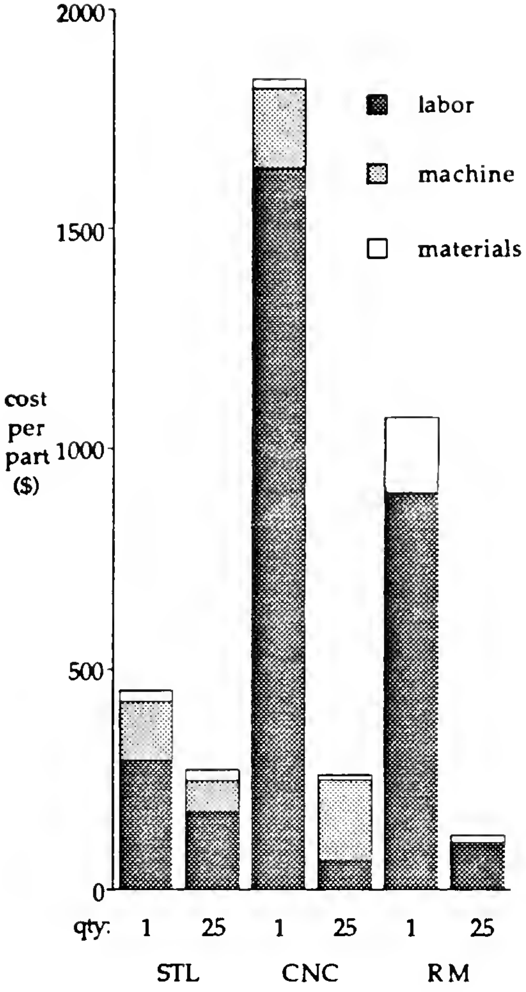

Figure 11: Components of Cost

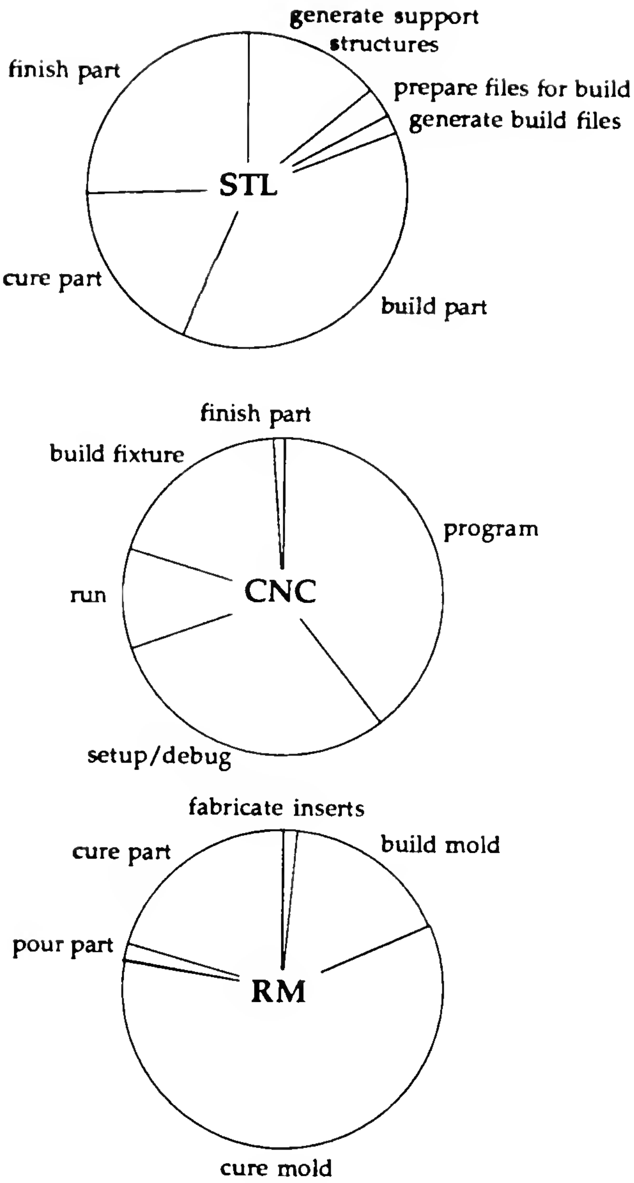

Figure 12: Process Components as a Fraction of Time (lot size of 1)

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6. APPENDIX A - THE ATTRIBUTE IMPORTANCE SURVEY

Name:

Date:

LoB:

Please return to:
Matthew Wall
2-4-EP mail code: 35326

Primary Function (choose one):

- ○ engineering
- ○ design
- ○ management
- ○ other____________________________

Primary Discipline (choose one):

- ○ mechanical
- ○ electrical
- ○ optical
- ○ other____________________________

At what stage(s) of the product development cycle are you involved with prototype design, fabrication, or assembly?

- ○ concept development
- ○ product engineering
- ○ pre-production

Given that prototypes are built for different purposes, how important (on average) are the following attributes in your prototype *parts* during the phases of product development listed to the right?	*concept*			*engineering*			*pre-prod*		
	unimportant		very important	unimportant		very important	unimportant		very important
stiffness or compliance	○	○	○	○	○	○	○	○	○
dimensional accuracy	○	○	○	○	○	○	○	○	○
geometry	○	○	○	○	○	○	○	○	○
surface finish	○	○	○	○	○	○	○	○	○
hardness	○	○	○	○	○	○	○	○	○
manufacturing tolerance variability	○	○	○	○	○	○	○	○	○
weight	○	○	○	○	○	○	○	○	○
melting temperature	○	○	○	○	○	○	○	○	○
opacity or transparency	○	○	○	○	○	○	○	○	○
color	○	○	○	○	○	○	○	○	○
conductivity or resistivity	○	○	○	○	○	○	○	○	○
method of integration into system	○	○	○	○	○	○	○	○	○
strength	○	○	○	○	○	○	○	○	○
feature definition	○	○	○	○	○	○	○	○	○
overall appearance	○	○	○	○	○	○	○	○	○
functionality	○	○	○	○	○	○	○	○	○
cost	○	○	○	○	○	○	○	○	○
turnaround time	○	○	○	○	○	○	○	○	○
manufacturing process	○	○	○	○	○	○	○	○	○
assembly procedure	○	○	○	○	○	○	○	○	○

Please list some critical-to-function features typically found in your prototype parts.